

APPLICATION

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**FOR**

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**ON**

2-D PROJECTILE TRAJECTORY CORRECTION SYSTEM AND METHOD

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## **2-D PROJECTILE TRAJECTORY CORRECTION SYSTEM AND METHOD**

### **BACKGROUND OF THE INVENTION**

#### **Field of the Invention**

5           This invention relates to launched projectiles in general, and specifically to a two-dimensional correction system and method for correcting the range and deflection errors in an unguided spin or fin stabilized projectile.

#### **Description of the Related Art**

10           Modern warfare is based on mission speed, high per round lethality, and low possibility of collateral damage. This requires high precision. Unguided artillery shells follow a ballistic trajectory, which is generally predictable but practically results in larger misses at ranges greater than 20 miles due to variations in atmospheric conditions; wind speed and direction, temperature and precipitation, and variations in the weapons system;  
15           manufacturing tolerances, barrel condition, propellant charge temperature and gun laying errors. As the ballistic range increases, the potential impact of the projectile variation grows until the projectile delivered lethality is too low to effectively execute the fire mission.

            Precision in such weapons comes at a high cost. Fully guided rounds such as  
20           ERGM, XM982 and AGS LRLAP cost \$25,000.00 to \$40,000.00 a piece. These solutions are essentially a gun-fired guided missile that uses GPS/IMU technology to precision guide the missile to the target. Such high cost systems are not feasible to modify the millions of artillery rounds in the existing inventory or to be integrated into the design of new artillery rounds.

25           What is needed is a system that can provide in-flight projectile trajectory correction more simply and less expensively than a guided projectile. Preferably the system can be used to modify the existing inventory. The system should be safe from electronic jamming, which is likely in a combat environment. The system should improve accuracy so that the corrected projectiles can be used effectively for targets at  
30           ranges in excess of 20 miles.

There are a number of possible implementations that have been developed, typically as modifications to the fuze kit. These fall into the following categories of a 1D corrector; a kit that corrects either Down Range errors or Cross Range Errors or a 2D corrector, a kit that corrects both Down and Cross Range errors. Additionally, the 2D correctors can be implemented as a body fixed kit (where the kit rolls with the projectile body) or as a de-coupled kit, where the kit roll rate is different than the projectile body. The de-coupled 2D kit requires a roll bearing to de-couple the two elements.

The 1D Down Range corrector works by estimating the downrange decrement given that a brake is deployed to increase projectile drag and alter the ballistic trajectory of the projectile. This is a one time deployment decision. If atmospheric conditions change, the brake cannot adjust. The brake is easy to implement but also suffers in that cross range errors (~100 m DEP) are not reduced. The brake requires a slight change to the ballistic firing tables because the projectile must be aimed past the target. The brake is compatible with TRUTH (current projectile location) being supplied by either GPS or a Data Link from an external tracking source. See U.S. Patent 6,310,335 for an example of a 1D Down Range corrector.

The 1D Cross Range corrector works by estimating the cross range adjustment possible if a reduction in the projectile average roll rate is implemented to alter the ballistic trajectory of the projectile. This is a one time deployment decision. If atmospheric conditions change, the system cannot adjust. A one-time deployment of a fin or canard is easily implemented but suffers in that down range errors (>100 m REP) are not reduced. A slight change to the ballistic firing tables are required because the projectile must be aimed left of but closer to the intended target. This approach is compatible with TRUTH being supplied by either GPS or a Data Link from an externally tracking source.

The two above concepts can be used together to implement a 2D corrector to alter the projectile's ballistic trajectory (see U.S. Patent 6,502,786). Each mechanism independently implements the appropriate deployment decision. Each individually is a one time deployment decision. If atmospheric conditions change after deployment, the system cannot adjust. This is an easily implementable system but suffers in that it requires a substantial change to the ballistic firing tables to be used operationally.

The de-coupled 2D corrector works by estimating both the down range and cross range adjustment possible if a change in the average projectile body angle of attack is implemented. This can be a continuous correction. These systems suffer in that the de-coupling mechanism is bulky and the fuze outer mold line cannot follow the NATO STANAG shapes such that new and different ballistic firing tables are required to be used operationally. This system is also compatible with TRUTH being supplied by either GPS or a Data Link from an externally tracking source. See U.S. Patents 5,512,537; 5,775,636 and 5,452,864 for examples of 2D Cross Range correctors.

There remains an acute and present need to provide a 2-D corrector for accurately correcting both the range and deflection errors inherent in an unguided spin stabilized projectile without having to modify the ballistic firing tables. The corrector should be simple, reliable, low power and inexpensive and capable of being retrofit to existing projectiles.

#### SUMMARY OF THE INVENTION

The present invention provides a 2-D correction system for accurately correcting both the range and deflection errors inherent in an unguided spin or fin stabilized projectile that can be used with existing ballistic firing tables and retrofitted to existing projectiles.

This is accomplished by intermittently deploying aerodynamic surfaces to develop a rotational moment, which create body lift that nudge the projectile in two-dimensions to correct the projectile in its ballistic trajectory. In low spin rate projectiles ("fin stabilized"), the rotational moment directly produces the body lift that moves the projectile. In high spin rate projectiles ("spin stabilized"), the rotational moment creates a much larger orthogonal precession that in turn produces the body lift that moves the projectile.

The aerodynamic surfaces are suitably deployed over multiple partial roll cycles at precise on (deployed) and off (stowed) positions in the cycle to nudge the projectile up or down range or left or right cross range until the desired ballistic trajectory is restored. Full downrange and crossrange control in all directions allows for the use of existing

firing tables. A fuze kit can be modified with a simple deployment mechanism and a pair of canards to retrofit existing projectiles. The 2-D corrector can be implemented as a body fixed or de-coupled kit, fixed or variable canard angle or attack, fixed or proportional canard deployment, continuous or windowed control to target, and forebody, mid-body or tail canard placement.

In an exemplary embodiment, a body fixed 2-D corrector includes a pair of pivot mounted canards and a deployment mechanism such as a voice coil with a centripetal spring incorporated into a modified fuze kit for attachment to a standard projectile. The canards are held at a fixed angle of attack and are either stowed or fully deployed. When stowed, the canards do not affect the ballistic trajectory. When deployed the canards create the rotational moment, hence lift that nudge the projectile. A TRUTH receiver such as GPS or a data link is incorporated into the kit's electronics to provide the current position of the projectile. A flight computer estimates deviations in the cross range and down range vectors to target are detected soon after launch and apogee, respectively, determines precisely when and how many times the canards must be deployed and stowed in partial roll cycles and controls the deployment mechanism accordingly. The flight computer may maintain continuous control to target of the intermittent deployment to keep the projectile on its ballistic trajectory or may make windowed adjustments early on for crossrange variations, after apogee for downrange variations and then once again at a certain time to target for both cases if required by a power budget.

These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings, in which:

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of an artillery shell having a modified fuze kit with a 2-D body fixed correction system in accordance with the present invention;

FIGs. 2a and 2b are section views of the modified fuze kit illustrating voice coil and centripetal spring mechanisms for intermittently deploying the canards to provide two-dimensional correction;

FIG. 3 is a system block diagram of the modified fuze kit;

FIG. 4 shows the effective angle of attack of the modified fuze kit and canards when deployed;

FIGs. 5a and 5b are moment diagrams that illustrate the reaction of high and low spin rate projectile to the creation of a rotating moment by deployment of a canard;

5 FIGs. 6a and 6b are plots of a control signal in the time domain and attitude domain;

FIG. 7 is a two-dimensional plot of a corrected ballistic trajectory and projectile dispersion;

FIG. 8 is a flowchart illustrating the use of the 2-D corrector system;

10 FIGs. 9a and 9b are plots of a projectile's 2-D corrected ballistic trajectory using continuous-to-target and windowed-to-target control; and

FIGs. 10a and 10b are diagrams of a 2-D corrector system implemented as mid-body wings and tail fins.

## 15 DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a 2-D correction system for accurately correcting both the range and deflection errors inherent in an unguided spin or fin stabilized projectile (artillery shells, missiles, EKV's) that can be used with existing ballistic firing tables and retrofitted to existing projectiles. This is accomplished by intermittently  
20 deploying aerodynamic surfaces to develop a rotational moment, which creates body lift that nudges the projectile in two-dimensions to return the projectile to its ballistic trajectory. In spin stabilized projectiles, the rotational moment causes a much larger orthogonal precession, which in turn moves the projectile. The aerodynamic surfaces are suitably deployed over multiple partial roll cycles at precise on (deployed) and off  
25 (stowed) positions in the cycle to nudge the projectile up or down range or left or right cross range until the desired ballistic trajectory is restored.

As shown in figure 1, an unguided spin stabilized projectile 10 includes a steel housing 12 and an explosive payload 14. A fuze kit 16 is threaded onto the housing. A standard fuze kit includes a fuse, a safe and arm mechanism, battery, an initialization coil  
30 and a flight computer. High spin rate projectiles are stabilized gyroscopically, i.e. by the spinning of the projectile itself. Low spin rate projectiles are stabilized by the addition of

fins to the airframe. As modified to provide 2-D correction, the fuze kit includes at least one canard 18 (shown here in deployed position), a deployment mechanism and a TRUTH receiver for providing the position and velocity vector of the projectile on its ballistic trajectory to the target. In general, this design allows different types of fuse kits, e.g. timed fuses, impact fuse, and delayed impact fuses, to be used with a standard housing and payload. The incorporation of the 2-D correction in the fuze kit allows the millions of projectiles in inventory to be easily retrofit. The 2-D corrector can be implemented as a body fixed or de-coupled kit, fixed or variable canard angle or attack, fixed or proportional canard deployment, continuous or windowed control to target, and forebody, mid-body or tail canard placement.

As illustrated in section views of a modified fuze kit 16 (figures 2a-2b) and a system block diagram (figure 3), modified fuze kit 16 includes the standard functionality provided by an initialization coil 20, an HOB sensor 22, a flight computer 24, a detonator 26, a safe and arm device 28, a booster charge 30, and a battery 32. Initialization coil 20 serves as an AC-coupled input port through which an artilleryman can quickly, roughly and safely program the fuze detonation instructions into the flight computer 24. For example, detonate on impact, detonate x seconds prior to impact, detonate when altitude is less than y feet, etc. HOB sensor 22 provides the information, e.g. altitude, to the flight computer that initiates the detonation sequence. The illustrated projectile, as is typical of most projectiles, includes three separate explosive charges: the payload 14, detonator 26, which is a primer charge that does not have enough energy to set off the payload, and a booster charge 30 that does have enough energy to ignite the payload. To prevent accidental detonation, the detonator 26 and booster charge 30 are separated by the safe and arm device 28. Ordinarily, the safe and arm device is rotated ninety degrees to isolate the detonator 26 from the booster charge 30. The flight computer initiates detonation by rotating the safe and arm device thereby providing a channel from the detonator to the booster charge. Immediately thereafter, the flight computer sets off detonator 26 sending sparks and flame through the safe and arm device to set off booster charge 30, which in turn burns hot and with sufficient energy to ignite the payload 14.

The modified fuze kit 16 further includes at least one pivot mounted canard 18 and a deployment mechanism 34. Flight computer 24 is provided with a TRUTH

receiver 25, e.g. a GPS receiver, and programmed to execute a flight control algorithm to control the intermittent deployment of canards 18 to nudge the projectile to its ballistic trajectory.

5 In an exemplary embodiment, the deployment mechanism 34 includes a voice coil 36 and surface forcing magnets 38 on the canards. The flight computer 24 alternately generates command signals that energizes voice coil 36 thereby creating an electromagnetic field that interacts with the surface forcing magnet's permanent magnetic fields to produce a repulsive force that drives the canards outward to a deployed position as shown in figure 2b and then produces an attractive force that pulls  
10 the canards inward to a stowed position as shown in figure 2a. Other mechanism such as hydraulic, pneumatic or combination thereof may be employed to deploy the canards. The voice coil mechanism is particularly attractive because it provides both the precise control required to intermittently deploy and store the canards and the efficiency required to operate on a tight power budget. The canards may be moved between deployed and  
15 stowed positions or may be deployed proportionally to change the amount of force to the projectile.

To further enhance power efficiency, the deployment mechanism 34 may include a centripetal spring 40 that balances the centrifugal force on the canards caused by rotation of the projectile. Without the spring the voice coil 36 would have to remain  
20 energized to produce an attractive force to prevent the canards from deploying, which would be very inefficient. However, the centrifugal force decreases as the spin rate is reduced. Consequently, at lower spin rates the voice coil would have to produce a larger repulsive force to overcome the difference between the centripetal spring force and the centrifugal force, again reducing power efficiency. To mitigate this problem, a  
25 deployment spring 42 is unlocked when the spin rate falls below a threshold to counter the centripetal spring 40. Ideally, the voice coil 36 should only need to be activated to deploy and stow the canards and then only with sufficient force to accelerate their mass and not to overcome either the centrifugal force or the centripetal spring force.

As shown in figure 4, to generate lift the boresight 50 of the projectile must form  
30 an angle of attack  $\alpha$  with respect to the wind. Tilting the canards 18 at an angle  $\delta$  creates an effective angle of attack  $\alpha_\delta = \alpha + \delta$  that generates more lift. For simplicity the canard



angle  $\delta$  is suitably fixed although it may be movable to provide another degree of control. Note, because the rotation of the projectile causes an apparent wind angle, lift can be generated even if the canard angle is zero.

As illustrated in figures 5 and 6, the flight computer intermittently deploys and then stows aerodynamic surfaces to develop rotational moments, which create body lift that nudge the projectile in two-dimensions to correct the projectile in its ballistic trajectory. These techniques use the physics of rotating projectiles to their advantage as compared to conventional air-brakes that fight against the physics of ballistic projectiles by creating drag to reduce projectile velocity or slow the roll rate of the projectile. The current technique is more efficient and more precise.

As shown in figure 5a, canards **18** are for purposes of illustrating the physics of the control system instantaneously deployed in the XZ plane with the canards (mass  $m$ ) canted towards the negative Y axis to produce a rotating moment **60** in the XY plane. A spin stabilized projectile **58** with a high roll rate  $\Omega$  **62** about the X axis will, to a first order approximation, react to the rotating moment **60** in the XY plane by precessing **64** in the XZ plane in response to a coriolis acceleration  $F_c$ , i.e.  $F_c = -2mV_x \Omega$ . The command and resulting body angles,  $\Phi_{cmd}$  and  $\Phi_{body}$ , measured with respect to each other and are  $0^\circ$  and  $90^\circ$ , respectively. This is a highly efficient technique because the amount of precession caused by the physics of spinning projectiles is  $\gg 100$  times larger than the rotating moment. Thus, very quick deployments of the canards can nudge the projectile on to its ballistic trajectory.

As shown in figure 5b, canards **18** are for purposes of illustrating the physics of the control system instantaneously deployed in the XZ plane with the canards canted towards the negative Y axis to produce a rotating moment **68** in the XY plane. A fin stabilized projectile **70** with a low roll rate **72** about the X axis will, to a first order approximation, react to the rotating moment **68** in the XY plane by rotating **74** in the XY plane. The command and resulting body angles,  $\Phi_{cmd}$  and  $\Phi_{body}$ , measured with respect to each other and are  $0^\circ$  and  $0^\circ$ , respectively. Although not as efficient as the creation of precession, this approach is still an improvement over conventional air brakes that control the projectile using drag. Thus, very quick deployments of the canards can nudge the projectile on to its ballistic trajectory.

As shown in figures 6a and 6b, the canards are not and cannot be deployed and stowed instantaneous. In practice, the canards are deployed and stowed over multiple partial roll cycles of the projectile, suitably within a single quadrant, to precess or “nudge” the projectile in the desired direction to correct for downrange or crossrange errors in the projectile’s trajectory. Deployment over a full roll cycle would cancel out any precession and simply cause drag. As shown in figure 6a, the flight computer issues a command signal **80** at a precise time to move the canards to a deployed state **82** and rescinds the command at a precise time to move the canards to a stowed state **84**. The flight computer issues the command signal over a plurality of cycles until the projectile is moved to its desired ballistic trajectory at which point the canards are stowed until further correction is required. Figure 6a shows the representation of a stream of the command signals about the roll axis. The signals induce a projectile body motion **86** in a direction normal to the average force.

In order to balance the requirements of full and precise 2D control of the projectile to the target against the reality of a limited power budget, intermittent deployment can be done in a couple ways. A projectile’s ballistic trajectory **90** in a base frame **92** is shown in figure 7. The projectile **94** is fired in accordance with a standard firing table for that projectile, range, wind conditions etc. Note, that high spin rate projectiles that rotate in a clockwise direction will naturally precess to the right so they must be aimed to the left of the target. As illustrated, the projectile’s ballistic trajectory **90** will have a statistical dispersion **96**, typically +/- 150 m downrange and +/- 50 m crossrange for a 14 Km launch, based on variations in the projectiles, firing conditions, and changes in wind and other atmospheric. To use the existing firing tables, the 2D control mechanism must be (a) able to adjust in all four directions and (b) able to provide a total guidance correction **98** that encompasses the projectile dispersion **96**.

Figure 8 illustrates an exemplary control sequence that the flight computer **24** may execute to intermittently deploy the canard(s) to nudge the projectile to its ballistic trajectory. The flight computer is initialized (step **100**) to load mission data and is powered up (step **102**) from the battery when fired from the cannon. Shortly after launch, the flight computer makes a cross range vector estimate (step **104**) by comparing the projectile’s current position and attitude provided by, for example, a GPS/IMU

system to the target coordinates in accordance with the firing table and determines whether correction is required (step 106). The flight computer checks to determine whether apogee has been detected (step 108). If so, the computer estimates the range based on current ballistic trajectory (step 110), calculates a down range error estimate (step 112), and determines whether correction is required (step 114). The computer generates the appropriate roll vector for command to cause the desired precessed body motion (step 116) and then controls the canards to deploy for an increment  $\Delta V$ , typically in one quadrant, starting at a precise time (step 118) to nudge the projectile back towards its ballistic trajectory. The canards are deployed repeatedly until the projectile is back on its trajectory. If apogee is not detected, the computer controls the canards just to compensate for crossrange errors.

As shown in figure 9a, a weapons system 120 launches a projectile 122 on a ballistic trajectory 124 according to an existing firing table towards a target 126. The flight computer is powered up at a time T1 immediately after launch and maintains continuous control throughout the rest of the flight until the projectile impacts the target. This approach provides maximum control but does require continuous power to determine and make any necessary corrections. Alternately, as shown in figure 9b, the flight computer may be powered up shortly after launch for a time increment  $\Delta T1$  to make initial adjustments for crossrange variations, again after apogee at a time increment  $\Delta T2$  to make initial corrections for downrange variations and then once again (or more) at a certain time to target for a time increment  $\Delta T3$ . This approach should provide adequate control and will use less power.

Although the 2-D corrector system has been described in detail with reference to spin stabilized projectiles and specifically designed into a modified fuze kit, it is equally applicable to missiles, EKV's and other fin-stabilized weapons systems. As shown in figure 10a, an airframe 130 has tail fins 132 that provide stabilization. In this case, the kit deploys the surfaces as wings 134 in a mid-body assembly 136 to provide correction. As shown in figure 10b, an airframe 140 has tail fins 142 that provide stabilization. In this case, the kit implements the surfaces as fins 144 in a tail assembly 146 to provide correction.

While several illustrative embodiments of the invention have been shown and

described, numerous variations and alternate embodiments will occur to those skilled in the art. For example, although the invention has been described in the context of a “body fixed” fuze kit it could also be implemented in a decoupled configuration. Such variations and alternate embodiments are contemplated, and can be made without  
5 departing from the spirit and scope of the invention as defined in the appended claims.